49 p.

OTS PRICE

XEROX $ 4.60 ph

MICROFILM $ 1.62 mf.

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ELECTRO-OPTICAL SYSTEMS, INC., Pasadena, California

HYDROGEN-OXYGEN ELECTROLYTIC REGENERATIVE FUEL CELLS

Prepared for

National Aeronautics and Space Administration
Western Operations Office
150 Pico Boulevard
Santa Monica, California

(NASA   Contract NAS 3-2781)

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1. INTRODUCTION

This report covers the first quarter of a nine month program to evaluate rechargeable hydrogen-oxygen fuel cells for orbital applications. It is assumed that the cells will be used as energy storage devices in conjunction with silicon solar cell converters. An important advantage of the hydrogen-oxygen cell for this application, is its potential for very high energy storage/weight ratios.

The aim of the first phase of this program was a study of the operating conditions for minimum system weight of fuel cell and solar energy converter. If a fuel cell is designed for operation at maximum power density, its weight will be minimized. The weight of the solar cells required, on the other hand, is a function of the fuel cell efficiency, which in turn is optimum at a minimum current density. A minimum system weight somewhere between these extremes is therefore suggested. Previous calculations, based on very approximate assumptions of system parameters, have shown that such a minimum does exist, and that it exists within a practical range of current density values. In addition to factors relating to the mechanical design of the fuel cell, the position of the minimum will be determined by such additional factors as orbit altitude, and the power/weight ratio of the energy converter. The present analysis is considerably more detailed than previous analyses have been. A particular mechanical design is described, and an assumed polarization curve is used, upon which all the calculations are made.

When all of the computations were made and the results graphed, several interesting facts were immediately evident. First, for minimum system weight, the optimum discharge current density for the fuel cell lies within a convenient range, and second, the system weight is a very weak function of the discharge current density over a rather broad range. This means that other factors can be used, in large part, to determine the optimum fuel cell design. Another point brought out by the analysis is that for minimum system weight, the fuel cell itself will operate between 11 to 29 watt-hrs/lb., depending on orbital altitude and total power requirements. Use of a thermal storage material, however, lowers these values to ≈ 7 to 13 watt-hrs/lb.

The parametric analysis has been done for five different orbital altitudes and two different power levels, a 100 watt system and a 500 watt system. It is shown in this report that the electrode diameter becomes troublesome for power outputs greater than 500 watts. For greater power levels, an appropriate number of 500 watt modules should be used. All aspects of a complete system can be scaled up almost exactly linearly.

The design of the 75-watt prototype is nearing completion, and construction will begin shortly. It will consist of a battery of six cells with six-inch diameter electrodes. The unit will be instrumented to supply information about cell voltage and temperature for each cell, in addition to gas pressure. Approximately 800 grams of stearic acid will be contained within the fuel cell battery in order to test the thermal storage concept for maintaining a constant operating temperature.

A power supply and cycler unit is being designed to simulate a 750 nautical mile orbit. The total period for this orbit has been calculated to be 113.5 minutes. A satellite in this orbit would be in total sunlight 76.0 minutes, and in either total or partial darkness 37.5 minutes.

2. WEIGHT RELATIONSHIPS

The system analysis has been made by first relating the component weights to the fuel cell electrode area, and then relating the latter to the pertinent operating parameters of the system. After this part of the analysis was completed, the weight relationships were programmed into an IBM computer, and all parameters pertinent to the problem were varied systematically. For a given orbit and discharge power, the optimum current density for minimum system weight can be determined. From this current density, the number and size of the cells can be calculated. The results of this analysis are given in Section 3.

2.1 Fuel Cell

The essential features of the fuel cell components are shown in Figs. 1, 2, and 3, and the complete module in Fig. 4. Two end plates, together with their supporting structures for stiffening, a pressure equalizer, and the required number of separators, spacers, electrolyte beds, and electrodes make up the basic fuel cell module. This unit, together with its case, will comprise the fuel cell.

The relations between component weights and electrode area for the fuel cell are given in the following. In the equations of this section, the symbols used have the following meanings:

t - Thickness, cm

v - Volume, cm^3

w - Weight, gms

A - Area, cm^2

r - Radius of Electrode, cm

ρ - Density, gm/cm^3

ρ_A - Area Density (Mass/unit Area), gm/cm^2

h - Height, cm

FIG. 1 FUEL CELL SEPARATORS

FIG. 2   FUEL CELL ASSEMBLY

REVISIONS

ZONE	REV	DESCRIPTION	DATE	APPROVED

LIST OF MATERIALS

QTY	ITEM	PART NO.	DESCRIPTION	SIZE	MATERIAL
1	32		CONAX PRES GLAND		
12	31	4110-12267	BOLT		
12	30	600-015-10	PARKER STATO SEAL		
6	29	4110-12266	GASKET		
12	28	4110-12265	SLEEVE - INSULATING		
12	27	4110-12264	WASHER - INSULATING		
12	26		FLAT WASHER	#10 NOM ID	ALUM
12	25		HEX NUT	#10-32	ALUM
1	24		WELD ASSY - HYD TANK		CRES
12	23		FILLISTER HD SCR	#6-32 X 1/4	CRES
1	22		CONAX PRES GLAND		
2	21		PIPE PLUG	1/8 NPT	CRES
6	20	4110-12262	ELECTROLYTE BED		
12	19	4110-12263	ELECTRODE		
1	18	4110-12261	HYD END PLATE		
5	17	4110-12253	SEPARATOR		
1	16	4110-12260	WELD ASSY - OXY END PLT		
1	15	4110-12259	WELD ASSY - OXY TANK		
1	14	250-212	DIAPHRAGM		BUTYL
1	13	2-14	PARKER O-RING		BUNA N 50 SHORE
1	12		PRESSURE TRANSDR		

QTY	ITEM	PART NO.	DESCRIPTION	SIZE	MATERIAL
4	11		SOC HD CAP SCR	#6-32 X 3/8	CRES
1	10	4110-12258	CLAMP RING		
1	9	1191-3 IG X #8	HELI-COIL INSERT		
8	8		SOC HD CAP SCR	#10-32 X 1/2	CRES
1	7	4110-12257	RETAINING RING		
12	6		HEX NUT	3/8-24	CRES
1	5	4110-12256	INSULATOR - FLANGE		
12	4	4110-12255	WASHER - INSULATING		
12	3		FLAT WASHER	3/8 NOM ID	CRES
12	2		HEX HD MACH BOLT	3/8-24 X 3 1/4	CRES
2	1	2-253	PARKER O-RING		VITRON

D | 4110-12268

TYP BOLT INSTALLATION
(CELL SUBASSY)

HYDROGEN

OXYGEN

HYDROGEN

TO BE FILLED AT ASSY
APPROX 30cc STEARIC ACID

FIG. 3
END VIEW OF END PLATE
STIFFENERS

HYDROGEN PORTING

BOLT HOLES

THERMAL STORAGE MATERIAL

RADIATOR FINS

O_2

H_2

O_2 TANK

H_2 TANK
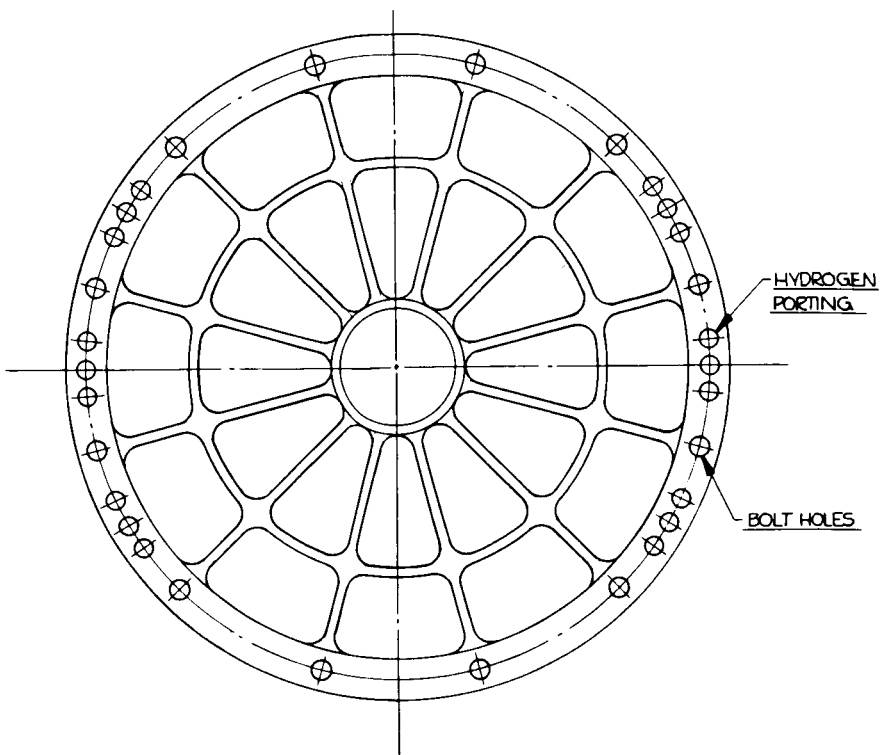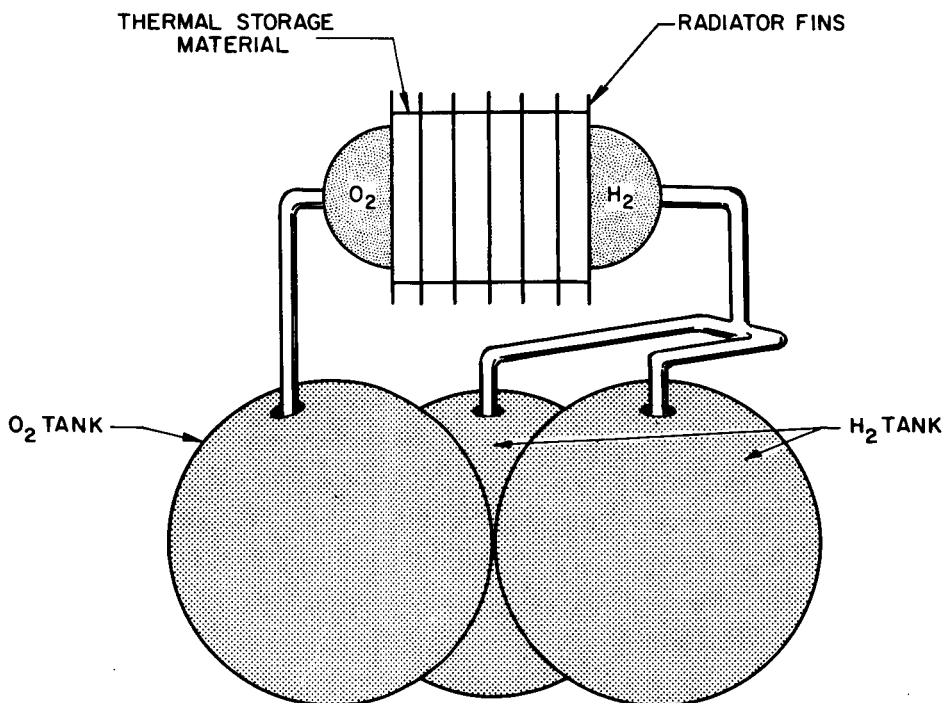
FIG. 4
COMPLETE FUEL CELL
Note: This drawing is a
schematic for the hypo-
thetical fuel cell battery
assumed for the analytical
program

Definitions, materials of construction, and brief descriptions are as follows:

2.1.1 Separators

The separator is defined as the component which separates one cell from the next, and which contains the gas manifolding and recesses for the electrodes. On one face it contains the recess for the hydrogen electrode of one cell, and on the opposite face the recess for the oxygen electrode of the adjacent cell. The separators will be made of magnesium with a thin plate of a sufficiently inert material (possibly nickel or epoxy) The weight of the plating material is not considered in the analysis, but this weight will be at least offset by the weight of magnesium removed for the gas distribution screen.

    a. Within electrode region

$$t = 0.060'' = 0.060/0.3937 = 0.1524 \text{ cm}$$
$$v = 0.1524 \ \pi r^2 = 0.4783 r^2 \text{ cm}^3$$
$$w_1 = 0.4783 r^2 \ \rho = 0.833 \ r^2 \text{ gm}$$

    b. Within manifold region

$$t = 0.100'' = 0.100/0.3937 = 0.254 \text{ cm}$$
$$A \text{ gross} = \pi (r + 1.27)^2 - \rho \ r^2$$
$$= \pi (2.54 \ r + 1.61) \text{ cm}^2$$
$$A \text{ net} = 0.4 \ A \text{ gross} = 3.20 \ r + 2.06 \text{ cm}^2$$
$$w_2 = \rho \ t \ A_{net} = 0.254 \ (3.20r + 2.06) \times 1.74$$
$$= 1.41 \ r + 0.910 \text{ gm}$$
$$w = w_1 + w_2 = 0.833 \ r^2 + 1.41 \ r + 0.910 \text{ gm}$$

The difference between A gross and A net in the manifold region is due to the holes for the gas manifolding.

2.1.2 Spacers

Spacers are the components which establish the spacing between the separators and provide sealing to prevent gas mixing. For the purpose of the analysis the material of construction is assumed to be Teflon.

$A_{net} = A_{net}$ for manifold region of separator $= 3.20\ r + 2.06\ cm^2$

$t = 0.935" = 0.035/0.3937 = 0.089\ cm$

$V = 0.285\ r + 0.183\ cm^3$

$w = V\rho = 0.627\ r + 0.402\ gm$

2.1.3 Electrodes

Porous nickel electrodes of 0.020" to 0.022" will be used. The electrodes used for hydrogen will be catalyzed with 5 mg. Pt + 5 mg Pd/cm^2, and those used for oxygen will have 10 mg. Pt/cm^2.

$A = \pi\ r^2$

$w = \pi\ r^2\ \rho_A$, where ρ_A is the area density

$\rho_A = 0.129\ gm/cm^2$, including 0.010 gm/cm^2 of catalyst.

$\therefore\ w = 0.405\ r^2\ gm$

2.1.4 Electrolyte

A 35 percent aqueous solution of KOH contained in an asbestos matrix is assumed for the weight analysis.

$A = \pi\ (r + 0.317)^2$

$V = t\ \pi\ (r + 0.317)^2$

$\rho = 2.44\ gm/cm^3$

$w = \rho V = 7.66\ t\ (r + 0.317)^2$

$\quad = (7.66\ r^2 + 4.85\ r + 0.766)\ t$

The radius of the asbestos used is 1/8 inch (0.317 cm) greater than that of the electrode. This is the sealing area for the asbestos. The ρ value includes 40 percent of the asbestos weight for electrolyte. The density of the asbestos has been determined in this laboratory to be 2.62 gm/cm^3, including the binder which it contains. The factor, t, in the above expression will have a minimum value determined by gas diffusion characteristics of the cell. Beyond

this it will be determined by the discharge time, since the latter will fix the necessary capacity of the cell. Several series of gas diffusion experiments have been performed so that the bed thickness could be related to t_D, the discharge time.

2.1.5 End Plates

The end plates are the module components between which the cells are secured. The front face of each plate is recessed to allow for a hydrogen electrode in one and an oxygen electrode in the other. The oxygen end plate differs from the hydrogen end plate by having a flange which extends beyond the manifolding region, and into the sealing area of the external case. Since the compression of the asbestos and spacers will exert a considerable internal force against the end plates, they are stiffened in a manner similar to that shown in Fig. 3 .

It is assumed that the height of each of the twelve stiffeners in the end plate can be represented by 0.5 r. Their combined area is then

$$A_1 = 12 \times 0.5 \; r \; (r + 1.27) \; cm^2$$

The area of the cover plate can be represented approximately by

$$A_2 / \; \pi \; (r + 0.6)^2 \; cm^2$$

The area of the outside ring stiffener is

$$A_3 \; 2\pi \; (r + 1.27)$$

The area of the small ring stiffener is

$$A_4 = 2\pi \; (0.1r)$$

This structure is built onto a part which is similar to a separator except that it is recessed for an electrode on one side only, and contains only six instead of twelve gas manifolding holes. To a sufficiently good approximation the area can be considered to be equal to that of an ordinary separator, so that

$$A_5 = \pi r^2 + 3.20 \; r + 2.06 \; cm^2$$

The total area is, therefore,

$$A = 12.28 \ r^2 + 21.49 \ r + 11.17 \ cm^2$$

Thickness is assumed to be 0.100" for all parts.

$$\therefore V = 0.254 \ A = 3.12 \ r^2 + 5.45 \ r + 2.84 \ cm^3$$

and the weight is

$$w = 1.74 \ V = 5.42 \ r^2 + 9.49 \ r + 4.94 \ gm.$$

2.1.6 Oxygen End Plate(Magnesium)

The oxygen end plate is exactly like the hydrogen end plate except for the flange which extends into the exterior mounting bolt circle. The width of the flange is assumed to be 0.3r. Its area is, therefore

$$A = \pi \ (1.3r + 1.27)^2 - \pi \ (r + 1.27)^2$$
$$= 2.17 \ r^2 + 2.39r \ cm^2$$

and its volume is

$$V = 0.254A = 0.550 \ r^2 + 0.606 \ r \ cm^3$$

and its weight is

$$w = 1.74 \ V = 0.948 \ r^2 + 1.055 \ r \ gm$$

When added to the remainder of the end plate assembly, which is identical to that of the hydrogen end plate, the weight becomes

$$w = 6.38 \ r^2 + 10.54 \ r + 4.94 \ gm$$

2.1.7 Pressure Equalizer

The pressure equalizer used for this analysis is a Teflon bellows mounted on one end plate. Its purpose is to maintain equal gas pressures throughout the system. A new design is presently being investigated utilizing a Bellofram collapsible diaphragm. The cross section is assumed to be

$$A_1 = \pi \ r^2$$

and the enclosed volume, V_{en}, is

$$V_{en} = \pi \ r^2 \ h$$

This volume will be set at one percent of the total gas storage volume. The volume of the material is

$$V = 2 \pi r h t$$

and if $t = 0.050"$, or 0.127 cm, then

$$W = 1.75 \, rh = 1.75 \, V_{PE} = 0.0175 \, V_{en}$$

where V_{PE} is volume of pressure equalizer and V_{en} is the enclosed volume of the gas storage containers. V_{en} can be calculated as follows:

$$1 \text{ eq. of } H_2 \text{ at S.T.P.} = 11,200 \text{ cm}^3$$

$$1 \text{ eq. of } O_2 \text{ at S.T.P.} = 5,600 \text{ cm}^3$$

$$\text{Total, at 400 psia and } 70^\circ C = 16,800 \times \frac{343}{273} \times \frac{1,469}{400}$$

$$= 775 \text{ cm}^3$$

This amount of the reactants will yield 96,500 amp-secs or 26.82 amp-hrs. = 26,820 ma-hrs.

$$V_{en} = \frac{775}{26,820} = 0.02890 \text{ cm}^3/\text{ma-hr}$$

and

$$V_{en} = \frac{n P_D t_D}{28} \times 0.02890 = 1.03 \times 10^{-3} \, n \, P_D t_D$$

$$W = 1.80 \times 10^{-5} \, m \, P_D t_D$$

2.1.8 Miscellaneous Hardware

Considered under the heading of miscellaneous hardware are nuts, bolts, and washers for the cell stack, the retainer ring for the pressure equalizer, retainer ring screws, exterior mounting bolts (which hold the two halves of the external case together) and connector tubing leading to the gas storage tanks. The internal bolts and retainer ring are magnesium, the external bolts are steel, and the connector tubing is aluminum.

a. Nuts (aluminum), and bolt heads (magnesium)
for cell stack.

$A = \pi (0.1r)^2 \ cm^2$

$t = 0.125" = 0.317 \ cm$

$V \cong 0.010 \ r^2 \ cm^3$

$w = \rho V = 0.027 \ r^2 \ gm$

If the bolt heads plus washers equal weight of
aluminum nuts, then the above weight, which is for a single nut, can
be multiplied by 24 to give their total weight.

$\therefore w = 24 \times 0.027 \ r^2 \ gm$

$= 0.65 \ r^2 \ gm$

b. Retainer ring (magnesium) for pressure equalizer.

If the width of the ring is 0.1r, then

$A = \pi (1.1r)^2 - r^2 = 0.6 \ r^2 \ cm^2$

Assume $t = 0.125" = 0.317 \ cm$

Then $V = 0.317 \times 0.6r^2 = 0.18 \ r^2 \ cm^3$

and $w = \rho V = 0.31 \ r^2 \ gm$

c. Retainer ring screws (aluminum)

$A = \pi (0.03r)^2 = 0.0009 \ \pi r^2$

$= 0.0027 \ r^2 \ cm^2$

Assume $\ell = 0.25" \cong 0.63 \ cm$

$V = 0.0017 \ r^2 \ cm^3$

$V \ (of \ caps) = 0.01 \ r^2 \ cm^3$

$V \ (total) = 0.012 \ r^2 \ cm^3$

$w = \rho V = 0.032 \ r^2 \ gm$

Total for 12 = $0.38 \ r^2 \ gm$

d. Exterior mounting bolts (steel)

For the shank

$A_1 = \pi (0.07r)^2 = 0.015 \ r^2 \ cm^2$

Assume $\ell = 1.25" = 3.17 \ cm$

$V_1 = 0.048 \ r^2 \ cm^3$

$w_1 = \rho V = 0.37 \ r^2 \ gm$

For the head and nut

$$A_2 = \pi (0.1r)^2 \cong 0.03r^2 \text{ cm}^2 \text{ for the head, and since}$$

the nut is assumed equal in weight, the two together would be $2A_2$.

Assume $t = 0.25" = 0.63$ cm (including washer).

Then

$$V_2 = 0.038 \ r^2 \text{ cm}^3$$

and

$$w_2 = \rho V = 0.30 \ r^2 \text{ gm}$$
$$\therefore \ w = w_1 + w_2 = 0.67 \ r^2 \text{ gm.}$$

The weight for all twelve would be $12 \times 0.67 \ r^2 = 8.0 \ r^2$ gm.

      e. Connector Tubing (aluminum)

      Assume tubing with 0.125" ID and 1/32" wall

for all cases. Further assume length proportional to electrode

area. The cross section area of the material is, then

$$A = \pi(0.238^2 - 0.159^2) \cong 0.0984 \text{ cm}^2$$

Assume

$$\ell = r^2 + 20 \text{ cm}$$

then

$$V \cong 0.10 \ r^2 + 2 \text{ cm}^3$$

and

$$w = \rho V = 0.27 \ r^2 + 5.4 \text{ gm.}$$

The total for all miscellaneous hardware is:

$$w = 9.7 \ r^2 + 5.4 \text{ gm}$$

2.1.9 Casing (aluminum alloy)

The casing consists of two hemispherical ends, a cylindrical middle section, and a mounting bolt flange. The surface area of the casing is given by

$$A_1 = 4\pi (r + 1.27)^2 + 2\pi \ell (r + 1.27)$$

where ℓ is the length of the cylindrical section. Assume ℓ is proportional ro r, and assume $\ell = 3r$. Then

$$A_1 = 31.5\, r^2 + 55.9\, r + 20.3\ cm^2$$

Assume

$$t_1 = 0.0625" = 0.159\ cm$$

Then

$$V_1 = 5.00\, r^2 + 8.88\, r + 3.22\ cm^3$$

and

$$w_1 = \rho\, V_1 = 13.5\, r^2 + 23.9r + 8.7\ gm.$$

The flange area is exactly the same as the flange area of the oxygen end plate, so that

$$A_2 = 2.17\, r^2 + 2.39\, r\ cm^2$$

Assume

$$t_2 = 1.00" = 2.54\ cm$$

where t_2 is the total thickness of the flange. That is t_2 includes the thickness of the flange from both halves of the casing. Then

$$V_2 = 5.50\, r^2 + 6.06\, r\ cm^3$$

and

$$w_2 = \rho V_2 = 14.86\, r^2 + 16.36\, r\ gm$$

and the total weight, w, is

$$w = w_1 + w_2 = 28.4\, r^2 + 40.3r + 8.7\ gm$$

2.1.10 Gas Storage Tanks

It will be assumed here that three equal-sized spheres, two for hydrogen and one for oxygen, will be used to contain the reactant gases. The weight analysis would be almost identical if only two spheres were used, with the hydrogen sphere twice as large. It is likely, however, that more efficient packaging will result with three equal-sized spheres.

A high strength titanium alloy will be assumed for these storage tanks. Fiberglass tanks have been considered, but it appears that in its present state of development fiberglass may be unsuitable for a regenerative fuel cell. The minimum thickness of a spherical gas storage container is given by the relation

$$t = \frac{rP}{2\sigma} \qquad (t \ll r)$$

where r is the radius of the sphere, P is the storage pressure, and σ is the tensile strength of the container material. The volume of the container material is given by

$$V_S = 4\pi r^2 \, t = 4\pi r^2 \, \frac{rP}{2\sigma}$$

$$= 2\pi r^3 \, \frac{P}{\sigma}$$

$$\therefore W_S = 2\pi r^3 \, P \, \frac{\rho}{\sigma}$$

One gram of H_2O formed electrochemically at 1.229 volts is equivalent to 56.69/18.02 = 3.143 kcal. = 3.659 watt-hrs.

$$\therefore 1 \text{ watt-hr} = \frac{1}{3.659} = 0.2743 \text{ gm } H_2O$$

$$\frac{0.2743}{18.02} = 0.01517 \text{ moles } H_2O$$

$$= 0.01517 \text{ moles } H_2$$

$$= 0.00758 \text{ moles } O_2$$

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The molar volume at 70°C is

$$22.4 \times \frac{343}{273} \times 10^3 = 28,130 \text{ cm}^3.$$

$$0.0157 \text{ moles} = 0.01517 \times 28,130$$
$$= 427 \text{ cm}^3 \text{ at } 760 \text{ mm and } 70^{\circ}\text{C}$$
$$0.00758 \text{ moles} = 213 \text{ cm}^3$$
$$\text{Total} = 640 \text{ cm}^3$$
$$W_S = 2\pi r^3 P \frac{\rho}{\sigma}$$
$$= 2 \times 480 \times 14.69 \times \frac{4.51}{195,000}$$
$$= 0.326 \text{ gm/watt-hr.}$$

where a titanium alloy of density 4.51 gm/cm^3 and tensile strength equal to 195,000 p s i has been assumed. This value is the theoretical minimum container weight for the reactant gases, but the actual weight is given by

$$W_S = 0.326 \frac{1.23F}{V_D \, \eta_i \, \eta_c f} \quad \text{gm/watt-hr}$$

where F is the safety factor, which is the ratio of the theoretical bursting strength to the maximum working pressure, V_D is the discharge voltage, η_i and η_c are the current efficiency and power conditioner efficiency, respectively, and f is the fraction of stored gases which can be used. This latter fraction can be expressed in terms of the upper and lower working pressures by the relation

$$f = \frac{P_{upper} - P_{lower}}{P_{upper}}$$

The values assumed are as follows:

$$F = 2.2$$
$$\eta_i = 0.95$$
$$\eta_c = 0.85$$
$$f = 0.90$$
$$V_D = 1.00 - 0.00143 \, J_D$$

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The molar volume at 70°C is

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The values assumed are as follows:

$$F = 2.2$$
$$\eta_i = 0.95$$
$$\eta_c = 0.85$$
$$f = 0.90$$
$$V_D = 1.00 - 0.00143 \, J_D$$

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Inserting these values and multiplying by P_D t_D yields (where P_D is in mw and t_D in hours)

$$W_S = \frac{P_D\, t_D}{826 - 1.18\, J_D} \quad \text{gms.}$$

2.1.11 The r-function can be calculated readily since

$$P_D = A_{tot} J_D\, V_{D,1}$$

where P_D is the total discharge power, A_{tot} is the total electrode area for all cells, J_D is the discharge current density and $V_{D,1}$ is the discharge voltage for one cell.

Therefore,

$$P_D = \pi\, r^2 n\, J_D\, V_{D,1}$$

and

$$r = \left[\frac{P_D}{n\pi J_D (1.00 - 0.00143 J_D)} \right]^{1/2}$$

2.2 Auxiliary Equipment

The auxiliary equipment is considered to consist of the thermal storage material, its casing, and the power conditioner.

2.2.1 Thermal Storage Material

A thermal storage system will be used in order to attain isothermal operation of the fuel cell. Heat generation within the cell varies with the power output, and also varies between charge and discharge. A compound will be used (probably stearic acid) whose melting point corresponds to the fuel cell operating temperatures. With the proper radiating area and emissivity, the thermal storage compound will melt during periods when the heat generated by the fuel cell exceeds the rate of heat rejection, and will freeze when heat generation is less than heat rejection. With the proper design, there should be two phases in equilibrium at all times. The fundamental equation relating heat generation on charge, on discharge and average to the charge and discharge times is

$$(H_D - H_R) \; t_D = (H_R - H_C) \; t_C$$

where

H_D = discharge heat generation rate

H_C = charge heat generation rate

H_R = mean heat generation rate

and

$H_D > H_R > H_C.$

Solving this equation for H_R yields

$$H_R = H_D F + H_C \; (1-F)$$

or

$$H_R = F \; (H_D - H_C) + H_C$$

where

$$F = \frac{t_D}{t_D + t_C}$$

The equation for heat generation in a fuel cell operating at constant volume is

$$-\dot{Q} = \frac{dn}{dt}\left[(\gamma-1)\ (H_m - RT) - \gamma T S_m\right]^*$$

when the conversion from calories to watt-hrs is made, the values for the parameters in this equation are as follows:

$$H_m = -79.42 \text{ watt-hrs/mole, at } 70^{\circ}C$$

$$G_m = -64.00 \quad " \quad "$$

$$S_m = -0.04520 \text{ watt-hrs/deg/mole}$$

and

$$RT = 0.7928 \text{ watt-hrs/mole}$$

$$\therefore H_D = \frac{dn}{dt}\left[(\gamma-1)\ (-80.21) + 15.51\gamma\right]$$

and

$$H_c = \frac{dn}{dt}\left[(\gamma-1)\ (78.63) - 15.51\gamma\right]$$

The factor dn/dt can be calculated readily since

$$\frac{dn}{dt} = \frac{i}{2 \times 96,500} = 5.18 \times 10^{-6}\ i$$

Also,

$$i = J_D A_1 n = J_D \pi r^2 n$$

$$\therefore \frac{dn}{dt} = 5.18 \times 10^{-6}\ J_D\ \pi r^2 \text{ moles/sec}$$

or

$$\frac{dn}{dt} = 0.0585\ J_D\ r^2\ n \text{ moles/hr}$$

The remaining term, γ, can be calculated as follows:

$$\gamma_D = \frac{V_{D,1}}{1.253} = \frac{1.00 - 0.00143 J_D}{1.253}$$

$$= 0.798 - 0.001141\ J_D$$

and

$$\gamma_C = \frac{V_{C,1}}{1.253} = \frac{1.41 + 0.00235\ J_C}{1.253}$$

$$= 1.125 + 0.001876\ J_C$$

*The symbols are explained in Report 4110-M-2.

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By inserting the expressions for dn/dt and γ into the equations for H_D and H_C these latter quantities can be calculated. The results are

$$H_D = J_D \, r^2 n \, (1.670 + 0.00640 J_D)$$

and

$$H_C = J_C \, r^2 n \, (0.00692 J_C - 0.4462)$$

The minimum weight of stearic acid necessary would be

$$W_{S.A.} = 18.06 \times 10^{-3} \, t_D \, (H_D - H_R)$$

where the factor 18.06×10^{-3} is the weight of stearic acid, in grams, to store 1 mw-hr of heat in the heat of fusion.

$$\therefore W_{S.A.} = 0.01806 \, t_D \, (1-F) (H_D - H_C)$$
$$= 0.01806 \, t_D (1-F) \, J_D \, r^2 n \left(2.116 + 0.00640 J_D - 0.00692 \frac{J_D F}{1-F} \right)$$

2.2.2 Casing for Thermal Storage Material

The thermal storage material is contained between two concentric cylinders in the assumed design. The inner wall is the aluminum fuel cell case, and the outer wall is magnesium. The cross section area of this annular space is

$$A_{net} = A_o - \pi (r + 1.59)^2$$

where A_o is the area enclosed by the outside casing. The volume of this annular space is

$$V_{net} = L A_{net} = 3r A_o - 3\pi r \, (r + 1.59)^2$$

where L is the length. The volume is also expressed as

$$V_{net} = \frac{W_{S.A.}}{\rho_{S.A.}} = \frac{W_{S.A.}}{0.847} = 1.180 \, W_{S.A.}$$

Also,

$$A_o = A_{net} + \pi (r + 1.59)^2 = \pi R^2$$

where R is the radius of the outer casing.

$$\therefore 3r A_o - 3\pi (r + 1.59)^2 = 1.180 \, W_{S.A.}$$

$$A_o = \frac{1.180\, W_{S.A.} + 3\pi r(r + 1.59)^2}{3r}$$

$$= 0.393\, \frac{W_{S.A.}}{r} + \pi(r + 1.59)^2$$

$$= \pi R^2$$

and
$$R = \left[0.1246\, \frac{W_{S.A.}}{r} + (r + 1.59)^2\right]^{1/2}$$

The circumference, C, of the outer casing is
$$C = 2\pi R$$

and the volume is
$$V = 2\pi R\, tL = 6\pi rRt$$

(since it was assumed that $L = 3r$)

and if the thickness of the outer casing is taken as 0.2 cm. in all cases, then
$$V = 1.2\pi rR$$

and the weight is
$$W_{OC} = 1.2\, \pi rR\rho = 6.55\, rR$$

$$= 6.55\, r\left[0.1246\, \frac{W_{S.A.}}{r} + (r + 1.59)^2\right]^{1/2}$$

The weight does not include the ends of the container, but only the cylindrical portion. In addition to the necessary end caps, a considerable amount of material is necessary because the thermal conductivity of stearic acid, or any other suitable material, is much too low to permit an acceptable temperature differential across it. The approximation will be made that the total container weight, including the end caps, will be four times the weight of the cylindrical portion calculated above, so that the total casing weight can be given by

$$W_C = 33r\left[0.1246\, \frac{W_{S.A.}}{r} + (r + 1.59)^2\right]^{1/2}$$

2.2.3 Power Conditioner

The weight analysis will be based on EOS designed power conditioning equipment. Its function is to maintain constant output voltage with variations in load. There are also small variations in output voltage from the fuel cell which are dependent upon the state of charge.

$$W_{PC} = KP_D \begin{cases} K = 9.1 \times 10^{-3} \text{ for } P_D = 1 \times 10^5 \\ K = 6.4 \times 10^{-3} \text{ for } P_D = 5 \times 10^5 \end{cases}$$

where P_D is expressed in mw. The power conditioner efficiency, η_c will be assumed to be 0.85 in the present analysis.

2.3 Energy Converter

Silicon solar cell converters are assumed in the weight analysis. Based on the present state of the art, a figure of 5 watts/lb. for solar cell panels appears justified for the analysis. The weight can be expressed as

$$W_{ec} = kP_T = k\,(P_D + P_C)$$

where P_C, P_D, and P_T are respectively, the charge, discharge, and total power from the panel. In order that the charging voltage will be the minimum while insuring that the cell is charged to the same extent that it is discharged during a cycle, the relation

$$J_C t_C = J_D\,t_D$$

must hold. The power output and input for the fuel cell will be

$$P_D = \pi r^2\, n\, V_{C,1}\, J_D$$

and

$$P_C = \pi r^2\, n\, V_{C,1} J_C$$

$$\therefore P_C = P_D\, \frac{V_{C,1}\, J_C}{V_{D,1}\, J_D}$$

This last equation is true only if the current efficiency is 100 percent. P_C must be increased because practical current efficiencies are less than 100 percent, and because of the inefficiencies in the power conditioner. The former efficiency is assumed to be 0.95 and the latter 0.85.

$$\therefore P_C = \frac{P_D V_{C,1} J_C}{V_{D,1} J_C\, \eta_i\, \eta_c} = \frac{P_D\, V_{C,1}\, J_C}{0.808\, J_D\, V_{D,1}}$$

and finally,

$$W_{ec} = 0.09072\, P_D \left[1 + \frac{\left(\frac{F}{1-F}\right)\!\left(1.41 + 0.00235\right)\frac{J_D\, F}{1-F}}{0.808 - 0.001155 J_D} \right]$$

2.4 Weight Totals

From the weight relationships given in this and the previous report the weight totals for the complete system can be expressed as follows:

Fuel Cell

$$W_{fc} = 49.1 \ r^2 + 58.9 \ r + 23.1 + n(1.74r^2 + 2.04r + 1.31)$$

$$+ \frac{1.423 \times 10^{-5} \ P_D t_D n}{(r + 0.318)^2} \ (7.66 \ r^2 + 4.85 \ r + 0.706)$$

$$+ 1.80 \times 10^{-5} \ n \ P_D t_D + \frac{P_D}{826 - 1.18 \ J_D}$$

Auxiliaries

$$W_{S.A.} = 0.01806 \ t_D \ (1-F) \ J_D \ r^2 n(2.116 + 0.00640$$
$$J_D - 0.00692 \ \frac{J_D F}{1-F} \ )$$

where $W_{S.A.}$ = the weight of stearic acid.

$$W_C = \left[33r \quad 0.1246 \ \frac{W_{S.A.}}{r} + (r + 1.59)^2 \right]^{1/2}$$

where W_C = the casing for the stearic acid.

$$W_{PC} = KP_D \begin{cases} K = 9.1 \times 10^{-3} \text{ for } P_D = 1 \times 10^5 \\ K = 6.4 \times 10^{-3} \text{ for } P_D = 5 \times 10^5 \end{cases}$$

where W_{PC} = the weight of the power conditioner.

Energy Converter

$$W_{ec} = 0.09072 \ P_D \left[1 + \frac{\frac{F}{1-F}(1.41 + 0.00235) \ \frac{J_D F}{1-F}}{0.808 - 0.001155 \ J_D} \right]$$

3. RESULTS OF THE OPTIMIZATION STUDIES

The expressions for the weight totals were programmed into an IBM-1620 computer. Orbital altitudes of 300,1000, 5000, 10,000 and 22,400 miles were used with current densities of 10, 20, 40, 60, 80, 100, 120, 140, 160, 180 and 200 ma/cm^2. The appropriate number of cells was used according to the step function in Fig. 5 . Calculations for only two different output power levels were used, however, because electrode diameters become troublesome above the 500 watt (at 28 volt) level. Figure 6 shows the electrode diameter as a function of the discharge current density necessary to give either 100, 500, or 1000 watts for an output of 28 volts. For power levels above 500 watts the appropriate number of 500-watt modules can be used and each component weight will scale up almost exactly in proportion to the discharge power.

Figures 7 through 16 give component and system weights as a function of discharge current density. One feature which is immediately evident is that the optimum current density (i.e., the current density which yields minimum system weight) ranges from 80 ma/cm^2 at the lowest orbit to 120 ma/cm^2 at the highest. The reason for this is due mostly to the much lower solar panel weight at the higher orbits. This allows operation at higher current densities while paying only a negligible penalty for the lower efficiencies. The solar panel weight drops off sharply with increasing altitude because of the rapidly decreasing value of F, the fraction of the orbit during which the fuel cell is discharging. At the highest orbit, the fuel cell is hardly on more than a trickle charge even for the highest discharge current densities. The charging potential would be even lower than that assumed here, since a linear charge polarization curve was used for all charge as well as for all discharge current densities. However, this refinement would yield a negligible correction to the panel weight.
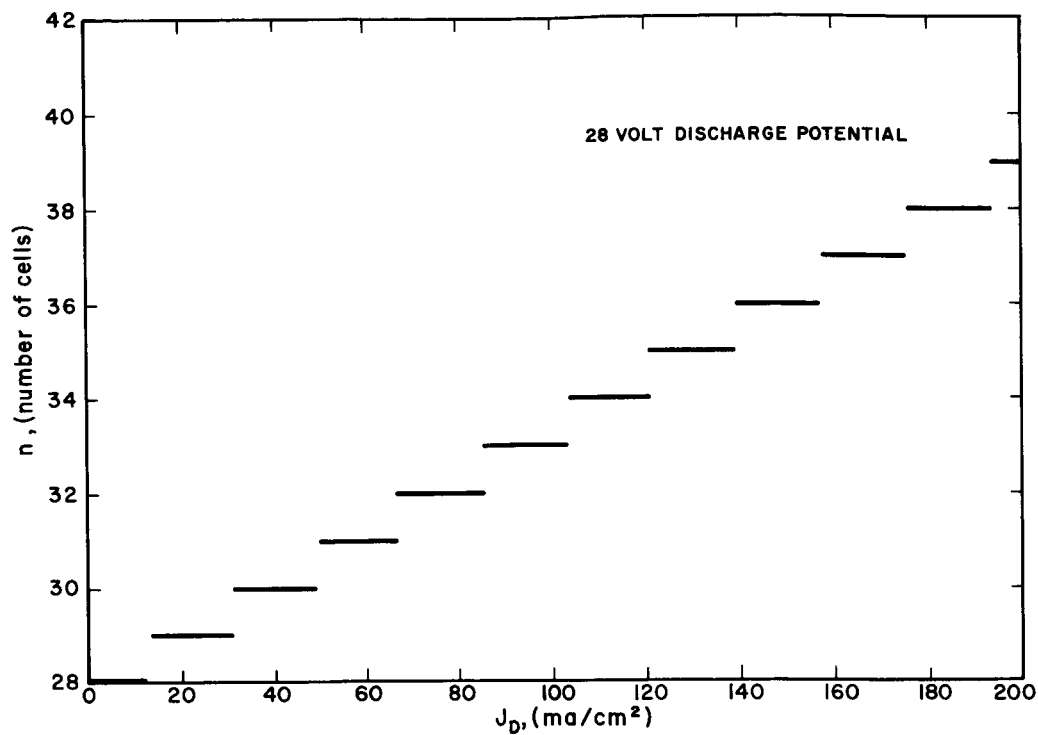
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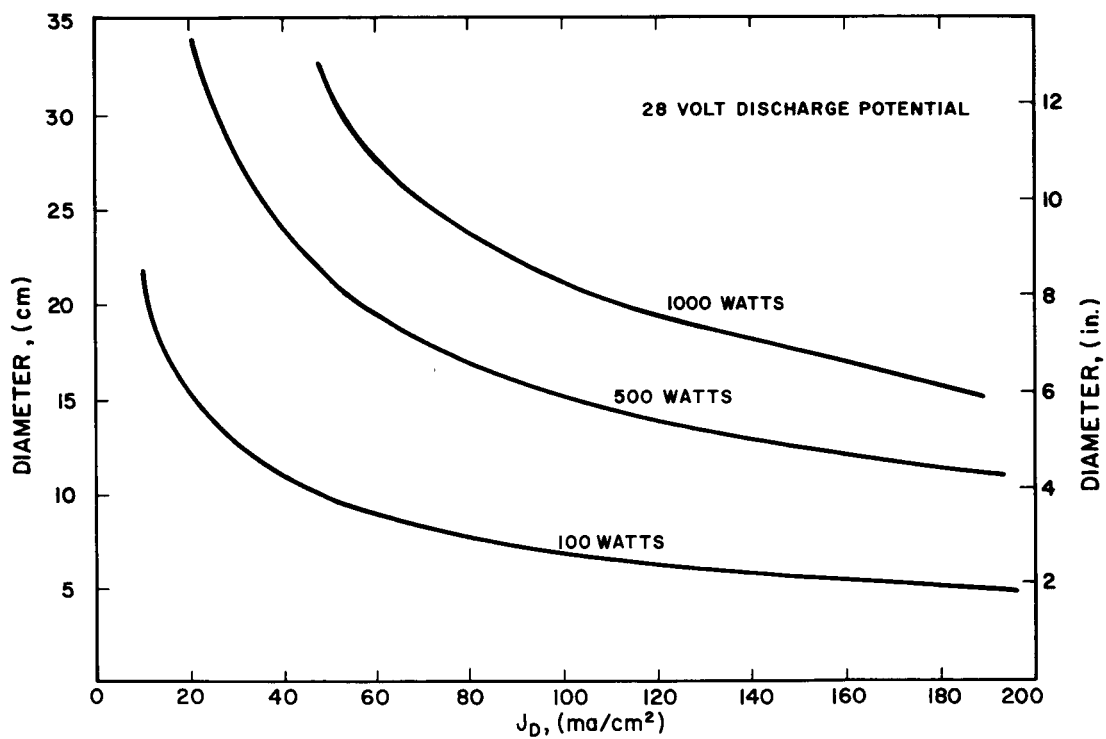FIG. 5   NO. OF CELLS REQUIRED AS A FUNCTION OF CURRENT
DENSITY

FIG. 6   ELECTRODE SIZE Vs. CURRENT DENSITY

Another fact which is immediately evident is that system weight is only a weak function of discharge current density within rather broad limits. In the design of a fuel cell this leaves a wide latitude in the selection of a discharge current density. It will very likely prove desirable to operate at somewhat less than the optimum current density in order to build in a large overload factor.

It is also quite noticeable in the curves of Figs. 7 through 16 that the thermal storage material (stearic acid, in this case) adds considerable weight to the system, particularly at the higher orbital altitudes. More thermal storage is necessary in higher orbits because of the greater variation between heat generation on discharge and heat generation on charge, when the heat generation is often negative. It should be remembered that the curves showing auxiliary weights really represent the weight of stearic acid plus its container, except for the power conditioner. The latter adds a constant 0.91 kg (2 lbs) for the 100-watt system or 3.2 kg (7 lbs) for the 500-watt system.

In terms of energy/weight ratios, it can be seen that for minimum system weight, the 100-watt fuel cell will yield 11.5 watt-hrs/lb at the lowest orbit and 25.3 watt-hrs/lb at the highest. The corresponding figures for the 500-watt system are 13.1 and 29.0. If the thermal storage system is used, the fuel cell energy/weight ratio is considerably reduced, especially for the higher orbits. The figure for the 100-watt system in the 300-mile orbit becomes 7 watt-hrs/lb; and for the 500-watt system in the 22,400-mile orbit, 13 watt-hrs/lb.
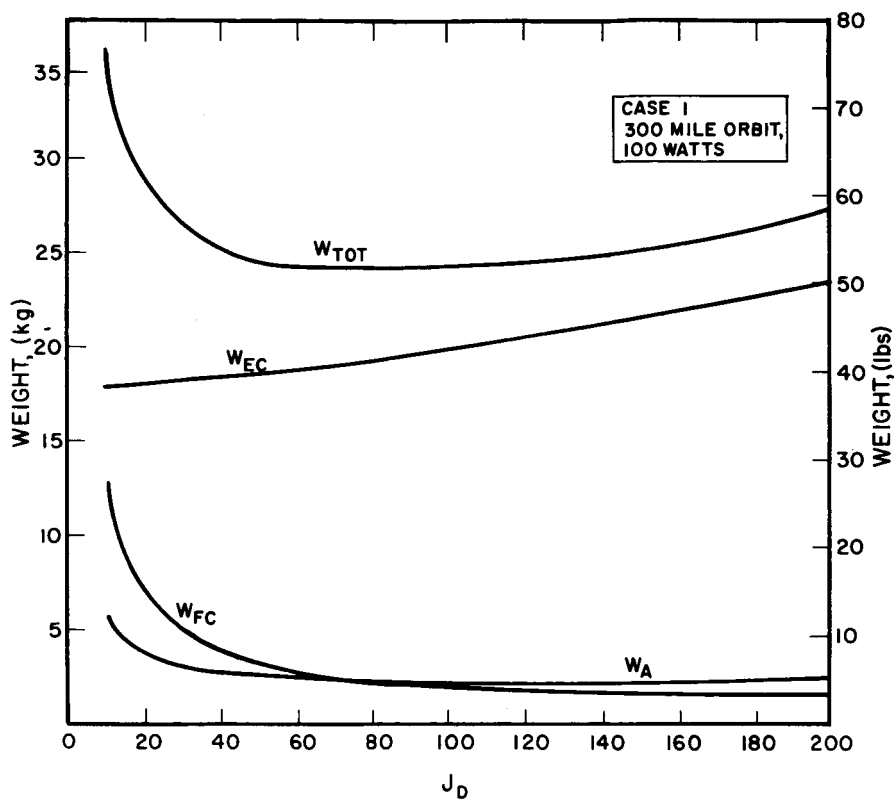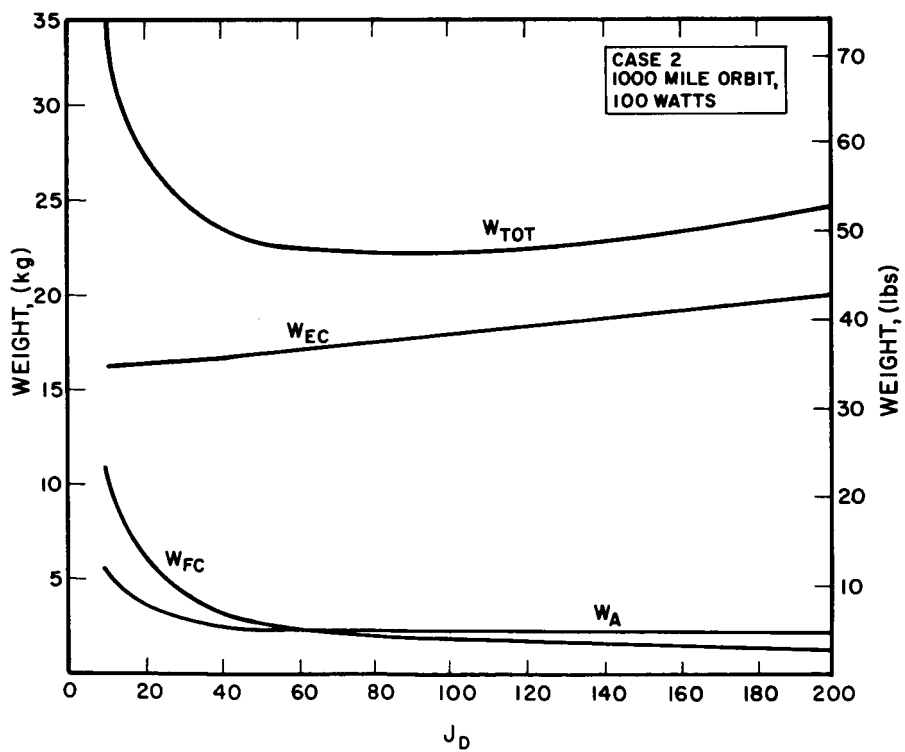
FIG. 7
COMPONENT AND SYSTEM WEIGHT
Case 1

FIG. 8
COMPONENT AND SYSTEM WEIGHT
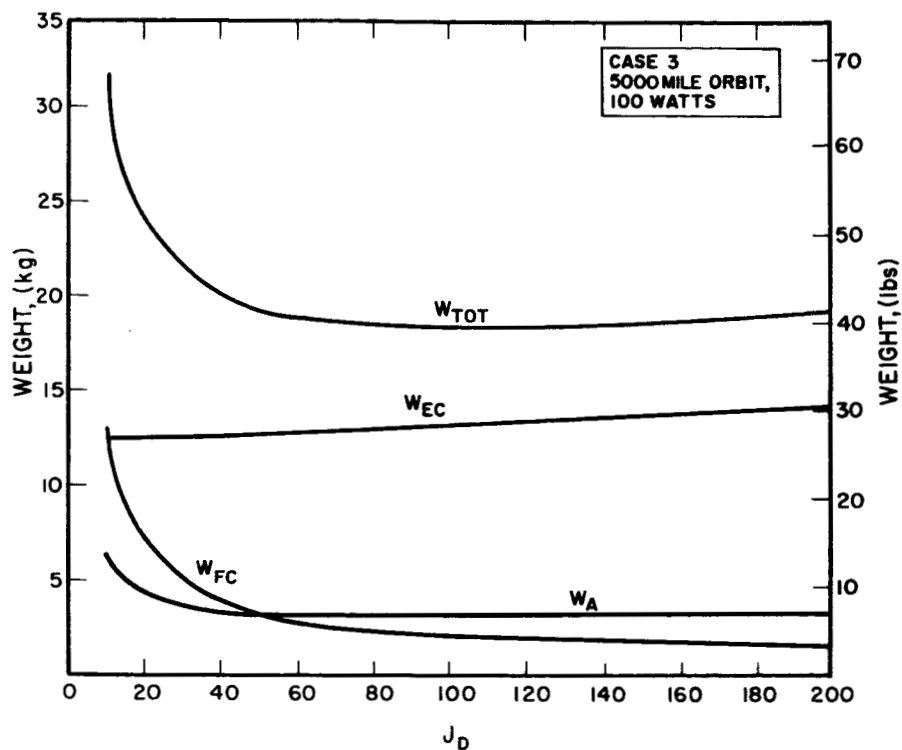Case 2

FIG. 9
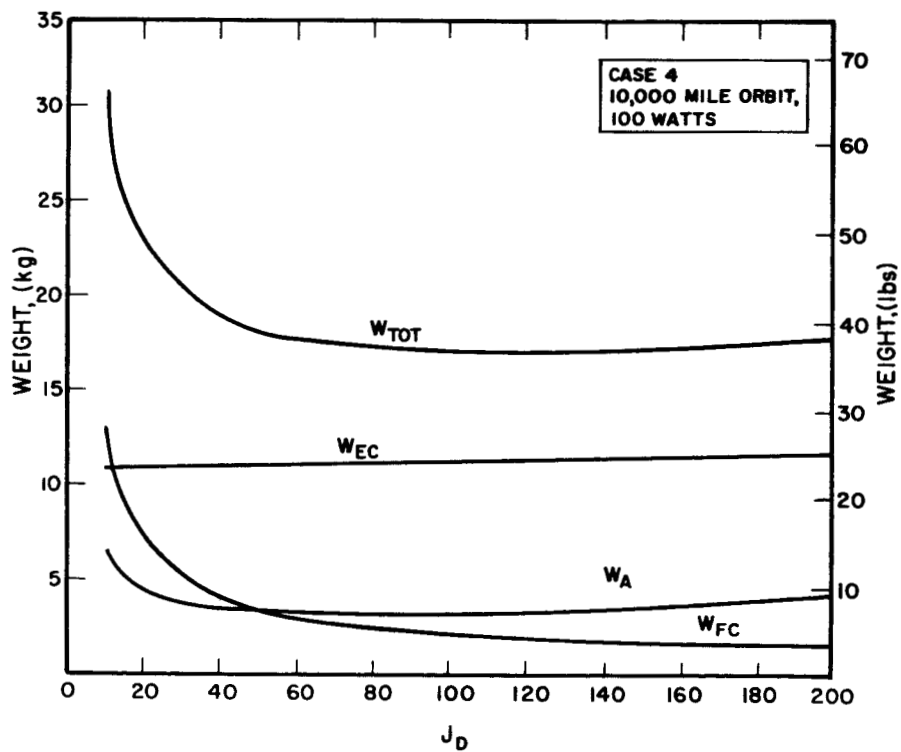COMPONENT AND SYSTEM WEIGHT
Case 3

FIG. 10
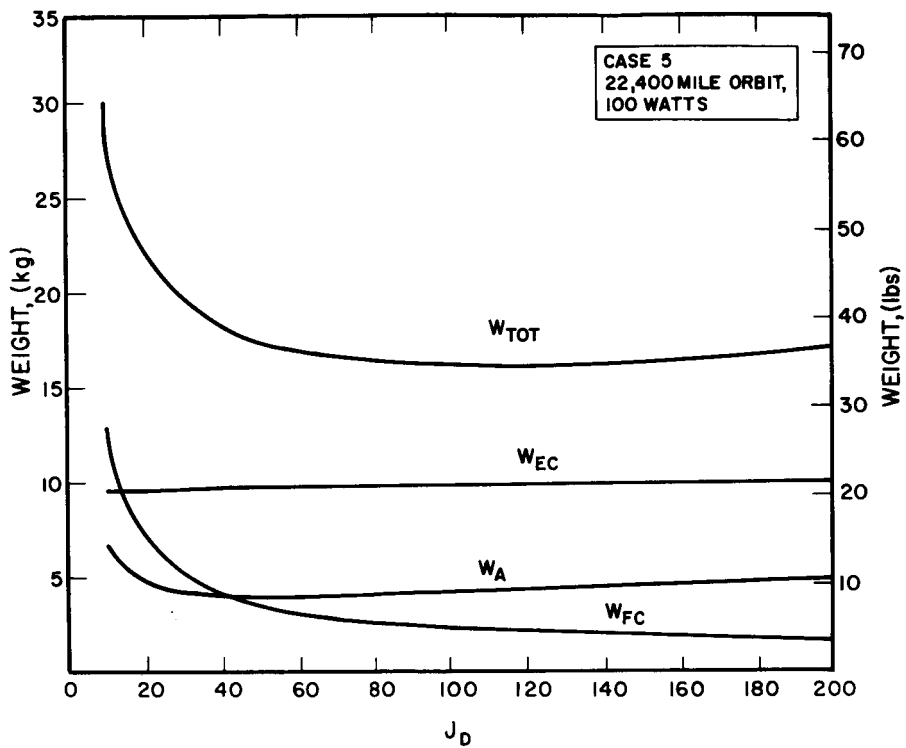COMPONENT AND SYSTEM WEIGHT
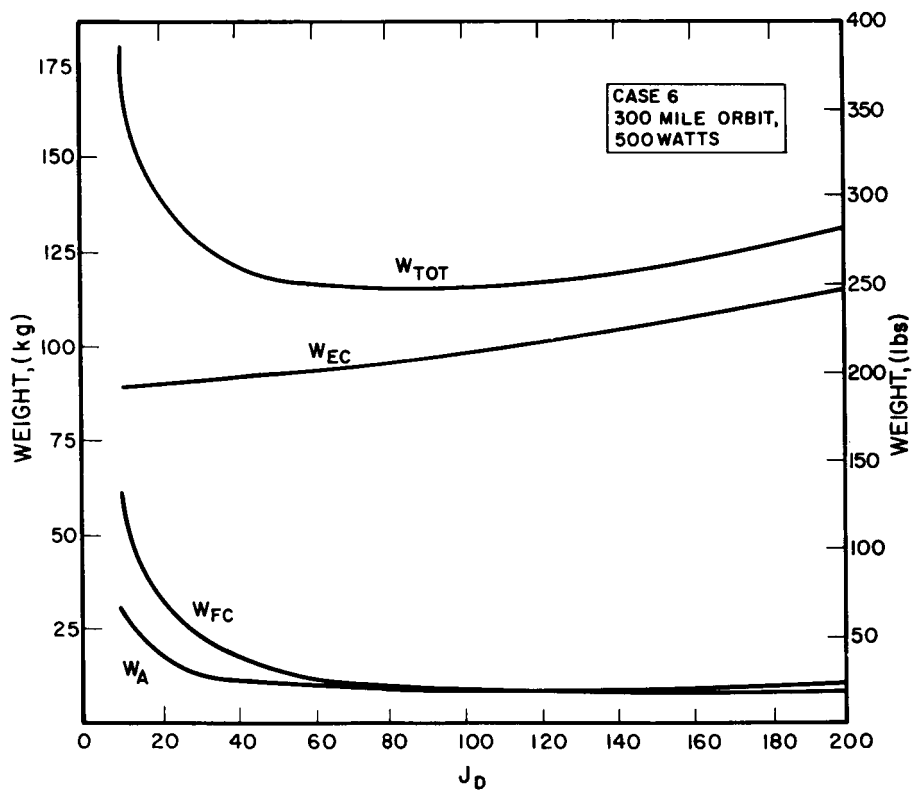Case 4

FIG. 11
COMPONENT AND SYSTEM WEIGHT
Case 5

FIG. 12
COMPONENT AND SYSTEM WEIGHT
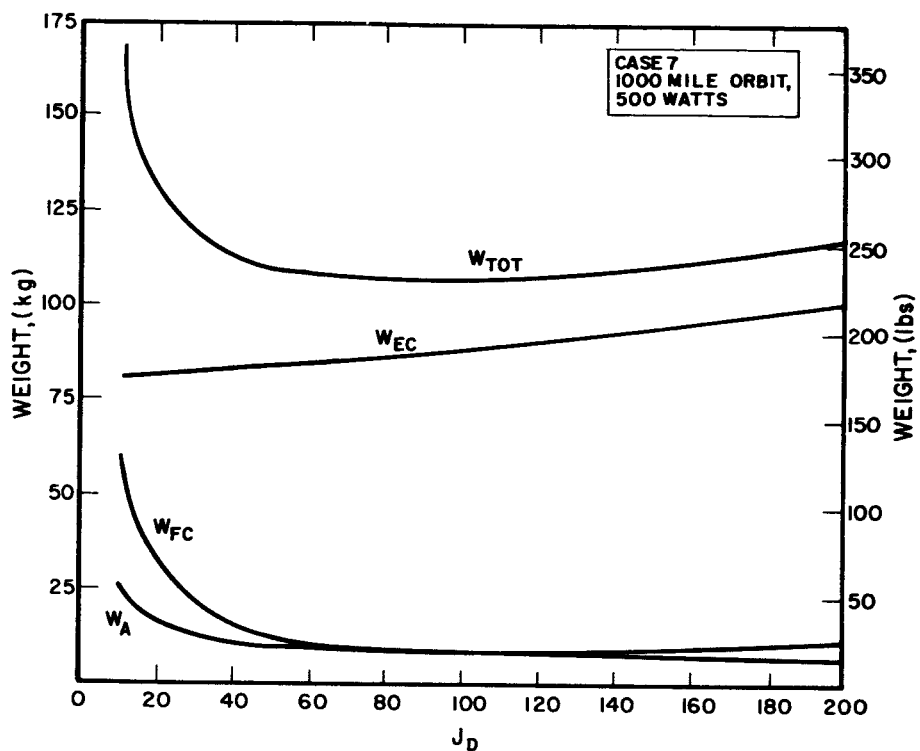Case 6

FIG. 13
COMPONENT AND SYSTEM WEIGHT
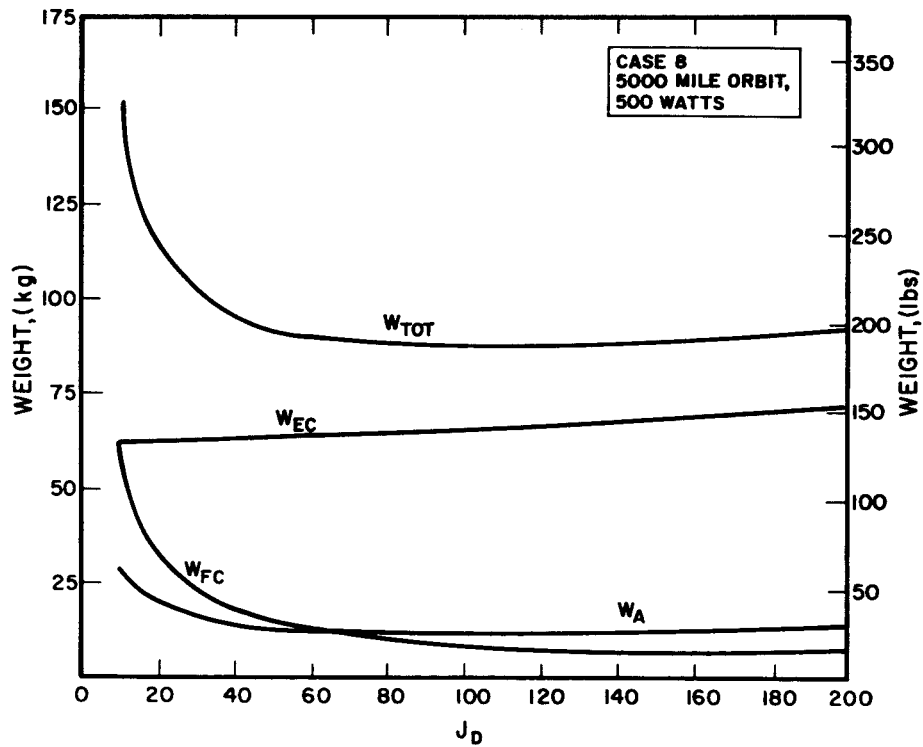Case 7

FIG. 14
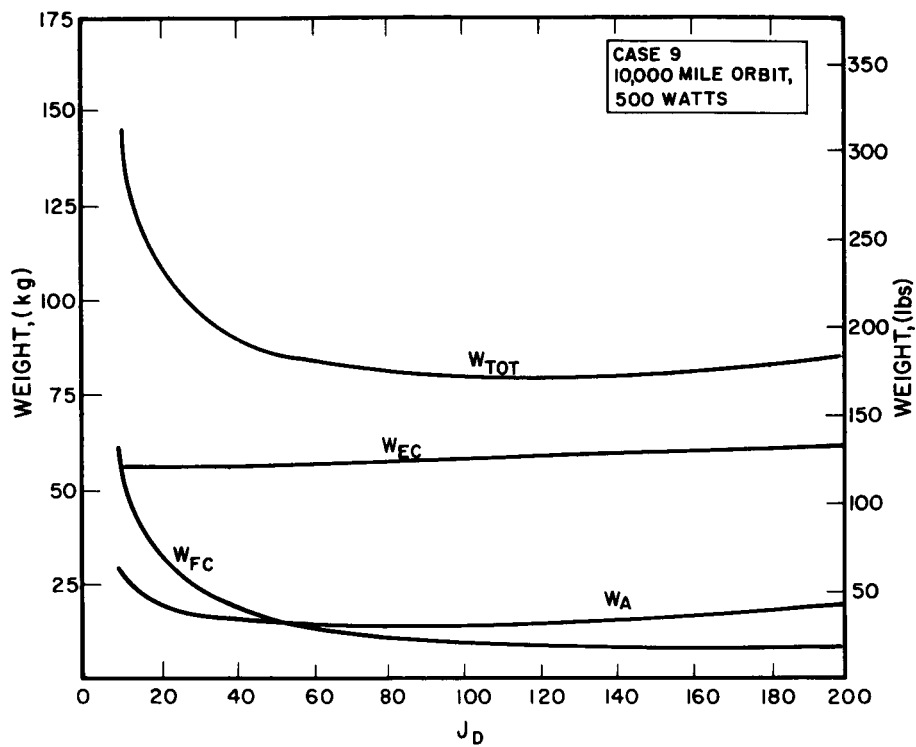COMPONENT AND SYSTEM WEIGHT
Case 8
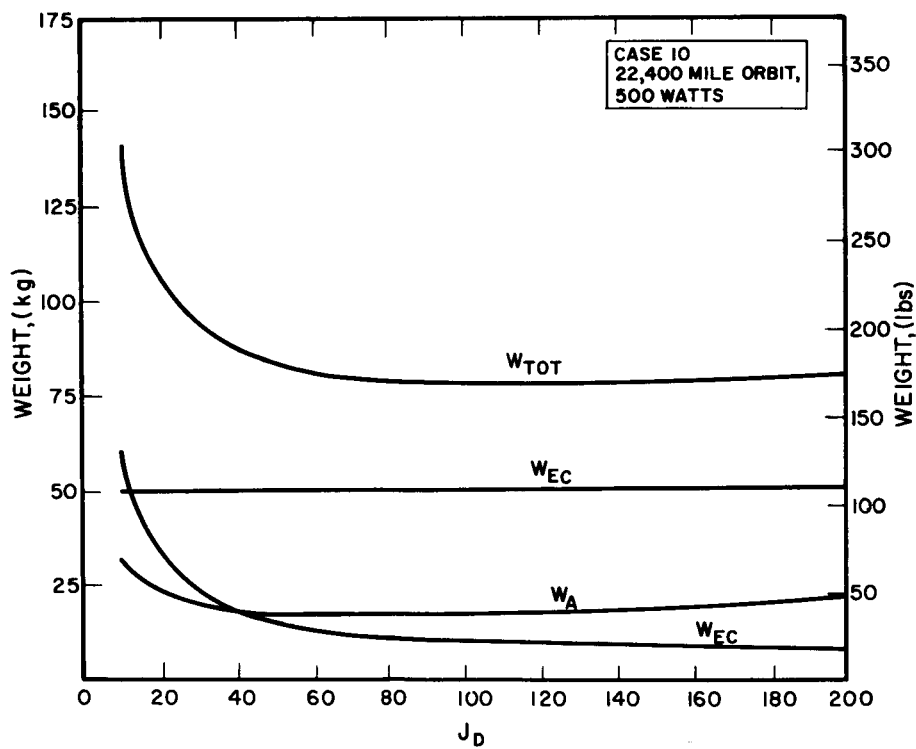
FIG. 15
COMPONENT AND SYSTEM WEIGHT
Case 9

FIG. 16
COMPONENT AND SYSTEM WEIGHT
Case 10

4. GAS DIFFUSION STUDIES

In order to set limits on the amount of water which can be electrolyzed from the electrolyte bed, a series of gas diffusion studies has been performed. The system for measuring diffusion rates has been designed so that equal gas pressures are maintained on both sides of the cell. Hydrogen is admitted to one arm of the system, and the gas which is used as the carrier gas (either oxygen or nitrogen) is admitted to the other. A mercury manometer of very high sensitivity was designed for the purpose of measuring the pressure differential between the two arms of the system.* A measured flow rate (usually between 10 and 30 ml/min) of the carrier gas is maintained across the back of the oxygen electrode while equal pressures are maintained in the two arms. After sweeping the back of the oxygen electrode the gas stream is passed through a silica gel drying tube and then into a reaction tube where the hydrogen is oxidized to water. The water is then adsorbed on silica gel and weighed.

Two different methods for oxidizing hydrogen have been used. In the first method, wire-form CuO is packed into a quartz tube (about 1 cm diameter and 40 cm long) which is kept in a furnace at 950°C. The gas stream passes over the copper oxide where the hydrogen is oxidized and then into a weighing tube containing silica gel. This method was checked by charging the cell while the gas diffusion measurements were in progress. In this procedure, the cell is opened to the atmosphere on one side while nitrogen is swept, at atmospheric pressure, across the other electrode and carried through the system as described above. The cell is electrolyzed so that hydrogen is introduced into the carrier gas stream. The

*This manometer was described in the final report for contract NAS 7-181.

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method proved accurate to within $\pm$ 10 percent in the charging range from 0.8 to 2.0 ma/cm^2. However, this method has three disadvantages, all of which have been overcome by the second method to be described. The disadvantages are (1) the quartz tube is attacked by the copper oxide fast enough so that only a few runs are possible with each tube; (2) water tends to condense in the tube between the furnace and the weighing tube; and (3) the start-up time is long due to the time required to heat the furnace.

In the second method a U-tube containing platinized asbestos in one arm and silica gel in the other replaced the furnace, the copper oxide, and the weighing tube. The entire process occurs at room temperature and, since the water is weighed in the same container in which it is formed, there is no problem of condensation before it reaches the weighing tube. In this case the carrier gas must be oxygen. This method for hydrogen determination was checked by producing hydrogen by the reaction between a KOH solution and high purity aluminum. If one uses more than 10 mg of aluminum per run (corresponding to 10 mg of water formed), this method is accurate to within $\pm$ 5 percent.

4.1 Effect of Pressure on Hydrogen Diffusion Rates

A determination of the effect of pressure on hydrogen diffusion rates was made. It can be seen by the results given in Table I that diffusion rates are a rather weak function of pressure. It will be noted that at very low pressures, the diffusion rates actually rise with decreasing pressure. This effect might indicate that gas pressures on the opposite sides of the electrolyte bed help the sealing of the asbestos.

It will also be noted that the results of several experiments are not given in the tables. When a new cell is first brought up to pressure, the apparent diffusion rate is almost invariably very high or very low. The reason is that gas diffusion rates across the asbestos bed are very sensitive to a differential pressure across

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the bed. This pressure differential cannot be avoided while bringing the pressures up.

4.2 Effect of State of Charge on Hydrogen Diffusion Rates

Major emphasis has been placed on determining the effect of state of charge on gas diffusion rates. The fuel cell used in these experiments has a 25.7 cm^2 electrode area and a compressed electrolyte bed 0.040" (1.0 mm) thick. The figure used in the analysis for amp-hours of storage capacity for unit volume was calculated on the basis of a 2 amp-hour state of charge for the experimental cell. It will be seen that at 2 amp-hours for the experimental cell, gas diffusion rates are acceptably low when a weight ratio of 0.7 is used for the electrolyte (i.e., electrolyte weight/asbestos weight = 0.7). The results are given in Tables II and III.

4.3 Oxygen Diffusion Rates

A limited amount of work was done on oxygen diffusion rates. It is readily apparent that these rates are negligible. The results are given in Table IV.

4.4 Effect of Temperature on Hydrogen Diffusion Rates

Two different attempts were made to determine temperature dependence on diffusion rates (once by the copper oxide method, and once by the platinum catalyst method). The variation with temperature in both cases was less than the uncertainty for a single measurement. These measurements were made at 25°, 40°, 50°, 60°, 70°, and in one case 80^oC.

TABLE I

EFFECT OF PRESSURE ON HYDROGEN DIFFUSION RATES AT $25^{\circ}C$

Electrolyte ratio = 0.4
State of Charge = zero
Copper oxide method

Expt. No.	Pressure psia	Diffusion Rate, Mg/kr.	Self-Discharge Rate ma/cm^2
2	55	4.0	0.77
3	65	1.4	0.27
4	75	1.4	0.27
5	85	3.6	0.65
6	95	2.0	0.40
7	105	2.0	0.40
8	115	1.6	0.31
9	115	3.0	0.58
10	45	6.2	1.19
11	45	5.6	1.08
12	55	3.8	0.73
13	65	2.2	0.42
14	65	0.6	0.12
15	75	0.4	0.08
16	85	0.0	0.00
17	95	1.6	0.31

TABLE II

EFFECT OF STATE OF CHARGE ON HYDROGEN DIFFUSION RATES AT $25^{O}C$

Electrolyte ratio = 0.6
Pressure = 65 psia

CELL #1

Expt. No.	State of Charge amp-hrs.	Hydrogen Diffusion Rate mg/hr.	Self-Discharge Rate ma/cm^2
2	0	0.3	0.03
3	0	0.6	0.07
5	1.0	0.6	0.07
7	2.0	9.8	1.14
8	2.0	5.5	0.64
9	2.0	3.6	0.42
13	2.5	37.2	4.3
14	2.5	31.0	3.6

TABLE III

EFFECT OF STATE OF CHARGE ON HYDROGEN DIFFUSION RATES AT 25°C

Electrolyte Ratio = 0.7
Pressure = 65 psia
Platinum Catalyst Method

CELL #2

Expt. No.	State of Charge amp-hrs.	Hydrogen Diffusion Rate mg/hr.	Self-Discharge Rate ma/cm^2
15	0	0.8	0.09
16	0	0.8	0.09
19	2.25	19.6	2.3
20	2.25	16.0	1.9

CELL #3

Expt. No.	State of Charge amp-hrs.	Hydrogen Diffusion Rate mg/hr.	Self-Discharge Rate ma/cm^2
21	0	0.0	0.00
22	1.5	1.8	0.24
23	1.5	1.4	0.22
24	2.0	18.0	2.45
25	2.0	19.2	2.22

CELL #4

Expt. No.	State of Charge amp-hrs.	Hydrogen Diffusion Rate mg/hr.	Self-Discharge Rate ma/cm^2
27	1.0	0.4	0.05
32	2.0	11.8	1.4
33	2.0	8.4	0.98
34	2.2	13.2	1.5
35	2.2	6.3	0.73
36	2.2	7.4	0.85
37	2.4	20.4	2.4
38	2.4	18.9	2.2

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TABLE IV

OXYGEN DIFFUSION RATES AT 25°C

Electrolyte Ratio = 0.7
Pressure = 65 psia
Platinum Catalyst Method

CELL #4

Expt.No.	State of Charge amp-hrs	Hydrogen Diffusion Rate mg/hr.	Self-Discharge Rate ma/cm^2
40	2.4	0.86	0.10
41	2.4	1.6	0.19
42	2.4	2.4	0.29
43	2.4	7.0	0.81
45	2.4	1.95	0.23
46	2.4	2.28	0.27
47	2.4	3.0	0.35
48	2.4	3.0	0.35

5. DESIGN OF EXPERIMENTAL FUEL CELL

The design for the 75-watt prototype fuel cell is in its final stages of completion. Close adherence to the design concepts assumed for the analysis has been maintained. Some minor departures have tended to make the unit lighter and some others have tended to make it heavier, but the total weight should prove to be close to that predicted in the analytical phase of the program. For example, the pressure equalizer is a little lighter than that which would have been predicted. The aluminum casing is also lighter since full hemispheres are not being used. The casing weight for the stearic acid is also lighter, but this weight saving would not be realized in an actual fuel cell battery since a battery of 32 to 35 cells would require an amount of stearic acid which is too much to contain within the end plates. The electrolyte weight is somewhat heavier than that assumed in the analysis. An electrolyte ratio of 0.4 gm. of 35 percent KOH electrolyte per gram of asbestos was assumed for the analysis, but the gas diffusion studies indicated that a ratio of 0.7 is desirable.

The tentative design drawings for the fuel cell battery are shown in Figs. 1, 2, and 3.

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6. CONSTANT CURRENT POWER SUPPLY AND CYCLER

A constant current power supply to be used in conjunction with a cycler is presently being designed. The cycler will be capable of simulating any orbit up to a charging time of three hours. For an orbital altitude of 750 nautical miles (862 statute miles) a discharge current of 19.0 amps is considered convenient. This implies 9.60 amps for the charge current density if 98 percent current efficiency is assumed. The total orbital period has been calculated to be 1.890 hours, or 113.5 minutes. Of this total orbital period, the discharge phase is 37.5 minutes, and the charge phase the remaining 76.0 minutes. Since the 6 inch diameter electrodes have an area of 182.5 cm^2, the charge and discharge current densities are, respectively, 53 ma/cm^2 and 104 ma/cm^2.

7. FUTURE PLANS

Work during the following months will be devoted to building the recharging power supply, and the completion of the detailed drawings for the fuel cell battery. Construction of the battery components will also be well advanced by the end of the next reporting period.

8. FINANCIAL STATEMENT

The expenditures for the first quarter were as follows:

Direct Labor Hours	1,375.75
Direct Labor Dollars	$ 6,742.54
Total Expenditures	$17,136.95

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